PB-221 291

PROTOTYPE CONSTRUCTION AND FIELD DEMONSTRATION OF THE PARALLEL CYCLONE SAMPLING TRAIN

Walter C. McCrone Associates, Incorporated

Prepared for:

Environmental Protection Agency

15 December 1972

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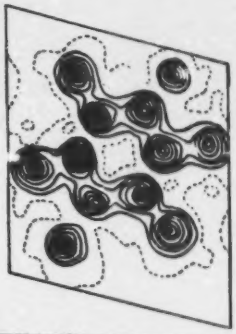

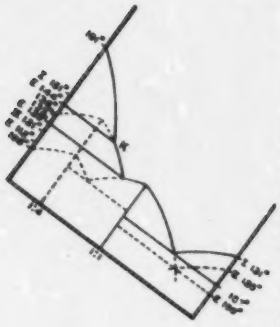

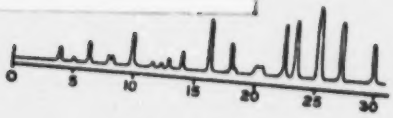

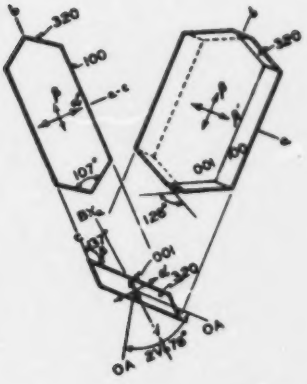

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BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-R2-73-220	2.	3. Recipient's Accession No. PB-221 241
4. Title and Subtitle: Prototype Construction and Field Demonstration of the Parallel Cyclone Sampling Train			5. Report Date: December 15, 1972 6.
7. Author(s)			8. Performing Organization Rept. No. MA 2425
9. Performing Organization Name and Address: Walter C. McCrone Associates, Inc. 2820 South Michigan Avenue Chicago, Illinois 60616			10. Project/Task/Work Unit No. 11. Contract/Grant No. 68-02-0258
12. Sponsoring Organization Name and Address: ENVIRONMENTAL PROTECTION AGENCY Research Triangle Park, North Carolina 27711			13. Type of Report & Period Covered: Final 14.

15. Supplementary Notes

16. Abstracts

A report is presented which describes in detail work done on a project to construct and test a newly designed prototype parallel-cyclone particle sampler. The parallel multicyclone sampling train consists of five main units: the sampling box, two heat exchangers and two air flow control boxes. The system components are all constructed from corrosion-resistant materials. The prototype construction is discussed in detail. Prototype testing was divided into five separate tasks. First, the theoretical and experimental operational characteristics of the three cyclone types were compared; next, the manifold functioning was experimentally verified so that any necessary design modifications could easily be made before final assembly, operational tests were made on the individual cyclones prior to assembly into the sampling train; the assembled sampling train was tested using the wind tunnel under simulated wet scrubber conditions; and fifth, the sampling train was field tested at a wet limestone scrubbing facility. These five tasks are described in detail. Finally, a summary of results and developments is presented.

17. Key Words and Document Analysis. 17a. Descriptors

Air pollution
Prototypes
Samplers
Cyclone separators
Air pollution control equipment
Construction
Tests
Field tests

17b. Identifiers/Open-Ended Terms

Parallel cyclone sampling train

17c. COSATI Field/Group 13B

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Unlimited	UNCLASSIFIED	30
	20. Security Class (This Page) UNCLASSIFIED	22. Price $3.00/$0.95

FORM NTIS-35 (REV. 3-72)

USCOMM-DC 14952-P72

Report to

Environmental Protection Agency
Durham Contract Operations
Research Triangle Park
North Carolina 27711

PROTOTYPE CONSTRUCTION AND FIELD DEMONSTRATION OF THE PARALLEL CYCLONE SAMPLING TRAIN

FINAL REPORT Contract 68-02-0258

Date: 15 December 1972

MA Number: 2425

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FINAL REPORT FOR CONTRACT 68-02-0258 (MA 2425)

INTRODUCTION

This final report is submitted in fulfillment of our contractual agreement under contract 68-02-0258, and summarizes the detailed information included in our four monthly status reports submitted throughout the contract period. The purpose of the contract was to construct and test a prototype parallel-cyclone particle sampler which we had designed under contract EHSD-71-25.

PROTOTYPE CONSTRUCTION

During the first two months of the contract the design of the parallel cyclone sampling train was reviewed, the necessary components to be purchased were ordered and the construction of the cyclones and by-pass filter was completed. Layout and assembly of the final prototype system was somewhat modified from the initial designs; assembly was initiated in June and completed in September. Although the design details of the unit have been detailed in our monthly reports, some of the important features are summarized here.

The parallel multicyclone sampling train consists of five main units: the sampling box, two heat exchangers and two air flow control boxes. Figure 1 shows how the cyclones and by-pass filter are combined with the gas pumping and control systems. The system components are all constructed from corrosion-resistant materials. For example, the cyclones and by-pass filter are nickel-plated brass, the condenser-evaporater-chiller sections of the heat exchangers are type 304 stainless steel, the gas pumps are Teflon coated; sour gas meters are used in place of regular gas meters, and stainless steel and Teflon tubing are used in the gas control systems.

The physical appearance of the sampler is illustrated in Figures 2, 3, 4 and 5. Figure 2 shows the relative size and shape of the by-pass filter holder and the three types of cyclones. Figures 3 and 4 show the assembled sampler unit and Figure 5 shows the assembled sampling train as

set up for laboratory testing.

Our initial design for the system included the construction of a 6-cfm gas pumping and metering system to be utilized in conjunction with the parallel cyclone samplers. It was originally thought that the pump, gas meter and the other associated accessories (i.e., pyrometer, manometer, orifice meter etc.) could be housed in the same container. However, the control box was estimated to weigh over 90 pounds, too heavy for field use. The initial configuration was somewhat modified and the final configuration is shown in Figures 1 and 5. The 6-cfm pump and gas meter were housed in the cyclone air-flow control box and the other accessories were housed in the filter air-flow control box.

PROTOTYPE TESTING

Prototype testing was actually divided into five separate tasks. First, the theoretical and experimental operational characteristics of the three cyclone types (T-1B, T-2A and T-3B) were compared. Second, the manifold functioning was experimentally verified. Third, so that any necessary design modifications could easily be made before final assembly, operational tests were made on the individual cyclones prior to assembly into the sampling train. Fourth, the assembled sampling train was tested using the wind tunnel under simulated wet scrubber conditions. And fifth, the sampling train was field tested at the TVA Wet Limestone Scrubbing Facility, Paducah, Kentucky.

Operational Characteristics Comparison

The variations of pressure drop (ΔP) and particle cut-off size were first calculated for different flow rates and then the cyclones were tested to determine the actual values under operation. The pressure drop across each cyclone was measured with a manometer and the instantaneous flow rates were measured with a calibrated orifice meter at various flow rates (Q) ranging from 0.2 to 4.5 cfm under room conditions of 72°F and a relative humidity of 60%.

In order to compare the actual pressure drops with the theoretically predicted values for the cyclones, the Q vs. ΔP curves for each have been plotted on Figures 6, 7 and 8. Figures 6 and 7 show that the actual

pressure drops across the T-1B and T-2A cyclones agree very well with the predicted values. In fact, the best fit curve of experimental data for T-1B very nearly coincides with the predicted curve. The actual pressure drop curve for T-2A parallels the theoretical one and differs by about 35% for flow rates ranging from 0.4 to 1.0 cfm. Although the actual pressure drops across the T-1B and T-2A agree with the predicted values, the actual and theoretical pressure drops across T-3B do not agree well; the actual pressure drops are about 15 times greater than the predicted values (Figure 8). The differences are attributed to the pressure drop across the manifold atop the T-3B cyclone, since this pressure drop was not considered during the calculations.

Manifold Testing

The manifold was designed to split the intake air into four controlled volumes; one into each of the three cyclones and one into the by-pass filter (see Figure 3). It must split the gas stream into four volumes in proportion to the required quantity of air flow for each cyclone. By varying the filter flow, isokinetic sampling can be achieved. The manifold was designed so that the particle loading and size distribution would be unchanged in each of the four gas streams. Two experiments were performed to test this requirement.

The tests were made at room conditions with various flow rates: one test with equal air flow through each of the four units (three T-1B and one T-2A cyclone) and another test with different flow rates. For equal rates, a flow of 0.75 cfm was chosen; and for the second set of conditions, the flow rates were set at 0.3, 0.6, 0.9 and 1.2 cfm so that the proportion of air volume was 1, 2, 3 and 4, respectively. Air flows through the four units were properly adjusted prior to the tests by using manometers and the actual pressure drop curves presented in Figures 6 and 7. Since only three manometers were available, the flow rates through only two units and the total flow rate through the whole system were continuously monitored.

In these tests, the flyash and limestone mixture of particles was generated by an acoustic dust feeder and then passed through the precollector, the manifold, the cyclones, and the by-pass filter. At the end of each test, the weight of particles collected by the precollector, the cyclones and by-pass

filter were weighed and their size distributions were measured. Although the experimental data did not agree perfectly with the theoretical requirement, the manifold worked reasonably well. The deviation of experimental and theoretical results was believed due to the slight variation of flow rates during the test. The flow rates through two of the units might have been slightly reduced during the test due to the pressure drop developed by the increasing dust loading of the filters.

The manifold functioning was also evaluated from the uniformity of particle size distribution passing through the four manifold outlets. The actual size distributions at the four manifold outlets agree very well under both sets of flow rates. Slight variations in the size distributions are believed due to errors in particle sizing and flow control variations.

In short, the results obtained from the manifold tests indicate that the manifold is capable of splitting dust-laden air into the four outlets without changing the size distribution and mass loading of particles significantly. The manifold was therefore considered well designed and no modifications were necessary.

Component Testing

In order to simulate stack conditions with a wind tunnel and to measure particle size distribution with a Climet particle counter, it was important to obtain information on the function of these two pieces of equipment under such conditions.

The tests indicated that the Climet and wind tunnel functioned properly. However, when we attempted to simulate the stack conditions at the inlet and outlet of the wet scrubber with the wind tunnel and obtain a calibration curve for each cyclone, the attempt was unsuccessful due to the following difficulties:

1) In simulating the outlet stack condition of 90.5% relative humidity, the probe was plugged with condensate and the optical sensing chamber in the Climet particle counter was flooded with water when the wind tunnel air was driven through the system. This caused the particle counter to

fail.

2) In simulating the inlet condition, 1.7% relative humidity, in which flyash and limestone particles were added to the wind tunnel, the sensing chamber of the Climet particle counter was overloaded with particles, and hence the counter also failed.

Due to these difficulties, particle size distribution measurement was shifted from the Climet particle counter to the Millipore π MC particle counter.

Wind tunnel conditions during component testing closely simulated the inlet condition of a wet scrubber: 300°F and 112°F of dry and wet temperatures, with 147 grams of particles added to the wind tunnel and circulating at 3000 fpm. The dust-laden air of the wind tunnel was drawn through the probe, passed through the cyclone and filter and then measured with an orifice meter. A 1/8-in. probe was used for the T-1B and T-2A cyclones, whereas a 3/8-in. probe was used for the T-3B cyclone. Various flow rates ranging from 0.3 to 3 cfm were used for the three cyclone models. Only one test was made under each condition with a sampling time of 30 minutes in each case. In order to compensate for the loss due to particle decay in the wind tunnel, about 3 grams of particles (flyash and limestone mixture) were added to the wind tunnel prior to each test. At the end of each test, the particles collected by the cyclone and the absolute filter were respectively weighed and their size distributions determined with the π MC counter.

Knowing the quantity and size distribution of those particles collected and of those that passed through the cyclone, the collection efficiency of each cyclone was determined. These results are plotted in Figures 9, 10 and 11.

The cut-off size of each cyclone — the particle size with 50% collection efficiency — was then easily obtained from these collection efficiency curves. The cut-off sizes for each of the cyclones at various sampling flow rates are presented in Table 1 and are plotted in Figures 12, 13 and 14. In order to compare the experimental and theoretical cut-off sizes of each cyclone,

the ΔP vs. X_{50} curves in figures 6, 7 and 8 were transformed into Q vs. X_{50} curves and superimposed on Figures12, 13 and 14. The theoretical cut-off sizes of these cyclones corresponding to the flow rates used in the tests are also presented in Table 1.

Since the 50% efficiency sizes (d_{50}) obtained from laboratory tests do not agree well with the design values, we were somewhat disappointed with the results obtained in this preliminary calibration test. Theoretically the d_{50} should decrease progressively as flow rate increases, as shown by the solid curves on these figures. However, this was not consistently observed in our tests. Also, the cross-overs of collection efficiency curves for a given cyclone under various test flow rates as appeared on Figure 9, 10 and 11 were not expected.

The differences between the theoretical and experimental d_{50} value obtained are believed attributable to the following factors:

1) Cyclone construction: Cyclone dimensions calculated by optimization procedures in cyclone design do not always give round numbers for machining. Therefore slight modifications were made during machining, particularly for the cyclone inlet and outlet dimensions. Since the inlet and outlet dimensions affect the collection efficiency of a cyclone, these design modification variances would cause the collection efficiency to vary somewhat.

2) Variation in particle density used in the cyclone design and experiment: A density of 2.4 gm/cc for the glass beads was assumed in the cyclone design, whereas the density of the flyash and limestone particles used in the experiments ranged from 1 gm/cc to over 6 gm/cc. Since d_{50} is a function of particle density, particle density variations would effect the resultant d_{50} value.

3) Variation in particle concentration and size distribution in the wind tunnel: Testing of the wind tunnel has shown

that the particle concentration and size distribution vary from time to time during experiments. Therefore, since the collection efficiency of a cyclone is related to mass loading and particle size, variations in particle concentration and size distribution in the wind tunnel would also vary the collection efficiencies.

4) Particle sizing and counting: Since the ⁋MC particle counter is accurate only for particles greater than 1 μm in size, particles smaller than 1 μm were manually counted by comparing their images with images of larger known particles. Therefore, an error could have possibly been introduced during particle counting and sizing.

5) Random error in experiment: Since only one test run was performed under each experimental condition and since a number of variables are involved in the determination of cyclone collection efficiency, the results obtained from each single test would not likely represent the true value. Additional testing would be required to obtain a statistically meaningful result.

Although the preliminary cyclone calibration data do not agree well with the theoretical predictions, the cyclones were capable of separating particles below 10 μm. We fell that whether the experimental data agree with the theoretical prediction is immaterial as long as the actual cyclone cut-off sizes are known. The data obtained in this preliminary calibration served as a guide in determining the approximate flow rates for the desired cut-offs in our laboratory prototype test.

Assembled Prototype Testing

The main purpose of the assembled sampling train laboratory test was to establish the actual cut-off values for the three cyclones at flow rates: 1.2 cfm for cyclone No. 1 T-1B; 0.5 cfm for No. 2 T-1B; 0.5 cfm for T-2A; 2.7 cfm for cyclone T-2B; and 0.5 cfm for the by-pass filter. The approximate size cut-off for each cyclone corresponding to these flow rates is 0.5, 1.4 and

6 μm, respectively. In addition, the laboratory prototype test was also intended to test the mechanical performance of the sampling train components: gas flow control and metering system, heating controls, temperature monitoring system etc.

The prototype tests were performed using the wind tunnel at the same conditions as in the individual component tests. The wind tunnel atmosphere closely simulated the inlet condition of a wet scrubber: 300°F and 112°F of dry and wet temperatures with 147 grams of flyash and limestone particles added to the wind tunnel and circulating at about 3000 fpm. A 1/2-in. heated probe with a 1/2-in. button hook sampling nozzle was used in the test. The operation procedure for the sampling train is briefly described as follows:

1. Weigh four 47 mm filters with a microbalance;
2. Mount the filters on the by-pass filter holder and the filter holders attached to each cyclone;
3. Assemble the sampling cyclones in the sampling box and connect the gas transport system;
4. Heat the sampling probe and sampling box to 250°F;
5. Adjust the flow rate through each sampling cyclone by referring to the pressure vs. flow rate curve for each cyclone as presented in Figures 6-8. To obtain 1.2 and 0.5 cfm air flow through cyclone T-1B and 0.5 through cyclone T-2A, a corresponding pressure drop of 26, 4.5 and 0.13 inches of water is required. Since the three cyclones draw air from the same inlet, flow rate adjustment in one cyclone would slightly vary the flow rate of others. Careful re-adjustment of the three flow rates through the three cyclones is therefore required. This can be achieved by nearly simultaneously adjusting the three flow control valves located on the top of the sampling box;
6. Record the initial readings of the two gas meters and then start the two pumps simultaneously;
7. Adjust the by-pass filter air flow to obtain isokinetic sampling conditions. This can be achieved by adjusting the pressure drop across the orifice meter to the corresponding pitometer reading.
8. Record temperature readings on the two gas meters;
9. Maintain a constant flow rate through each cyclone during

the sampling period;

10. At the end of each sampling period, reweigh all filters and all samples collected by each cyclone.

Particle size distributions of the cyclone and filter samples were determined by optical microscopy. The collection efficiency of each cyclone at the test flow rate was established based on the quantity and size distribution of particles collected by each cyclone and filter. Results of the collection efficiency calculations are plotted in Figures 15, 16, 17 and 18.

It is seen from these figures that the particle collection efficiency data obtained from the three runs for a given cyclone at a given flow rate fall short of a smooth curve, especially those for cyclones T-2A and T-3B. It is, in fact, difficult to fit a curve to the experimental data for these two cyclones. Despite these scattered experimental data, these figures indicate that the cut-off sizes of cyclones T-1B and T-2A are very close to the expected values. However, the cut-off size of cyclone T-3B, about 3.5 μm, was considerably smaller than the expected value of 6 μm. This is probably due to the fact that more air flow than the preset flow of 2.7 cfm was drawn through cyclone T-3B during the test. The observed actual flow rate through this cyclone was 2.93 cfm.

In summary, the results of the laboratory prototype tests show that the parallel multicyclone particle sampler is capable of separating particles in the desired size ranges provided the flow rate through each cyclone is well controlled.

Field Demonstration of the Parallel Multicyclone Particle Sampler

The field demonstration of the parallel multicyclone particle sampler was performed on October 16 and 17 at the TVA power station in Paducah, Kentucky. The sampling procedures in the field test were essentially identical to the laboratory prototype test. Three samples were taken, both from the inlet and outlet of the wet scrubber.

Knowing the weight of the particles collected by each cyclone and filter, the cumulative particle size distribution (by mass) of the aerosol drawn through the probe was calculated.

The results of the sampling train field test were very satis-

factory. According to the design criteria of the wet scrubber, 50 cumulative weight percent of the particles at the scrubber inlet should be smaller than 11 μm and all particles in the outlet should be less than 5 μm. This means that at the flow rate set in the field test a substantial fraction of particles would be collected by the precollector at the inlet. It also implies that practically no particles would be collected by the precollector and only a very small fraction of particles would be collected by cyclone T-2A at the outlet. These were verified by the field test data.

The anticipated performance of the parallel multicyclone particle sampler was also indicated by the distinct color of the particles collected by cyclone T-1B and its back-up filter. While the particles collected by the cyclone appeared gray, those collected by the back-up filter were black, indicating flyash and a fine oil mist, respectively.

Determination of particle size distribution by use of this sampler was also found to be very promising. The data indicate that the parallel multicyclone particle sampler is capable of providing sufficient data for the establishment of cumulative mass curves. The outlet size data obtained in Paducah fits very well to a straight line when plotted on arithmetic probability paper. This indicates the particle mass size distribution is "normal". Since a straight line can be both fairly well fitted to the inlet data plotted on an arithmetic probability and a log probability paper, the actual pattern of particle size distribution at the inlet was inconclusive.

SUMMARY

Although the parallel multicyclone particle sampler was found capable of providing sufficient data to establish particle size distribution of an aerosol, the application of the sampler was limited by sampling time. We found in the laboratory prototype tests and the field demonstration that the pressure drop across the back-up and by-pass filters developed quickly and a constant flow rate through each cyclone was maintained only in the first few minutes. This means that, if gravimetric analyses are desired, extended sampling times might be necessary and the sampler would therefore lose its accuracy in such instances.

To help correct this deficiency, modification of the sampling train is recommended. Although a pump of larger capacity would extend the sampling time, the increased volume and weight make this modification undesirable. The best way to extend the sampling time is to enlarge the filter holders from the present 47 mm to 3 inches.

Another important consideration in the performance of this sampler is an accurately known cut-off size for each cyclone at operational flow rates. In the laboratory prototype test, reproducibility of cyclone collection efficiency data was not very good due to the limitation of three test runs. Since the establishment of particle size distribution by the use of this equipment depends very much on the actual cut-off size of each cyclone, we recommend a more complete set of calibration experiments to measure the collection efficiency of each cyclone.

We acknowledge that the successful development of the prototype parallel multicyclone sampling train was through the direct efforts of Drs. Walter C. McCrone and Hsing C. Chang.

Respectfully submitted,

Donald A. Brooks

Donald A. Brooks
Executive Vice President

TABLE 1 Comparison of experimental cut-off sizes with theoretical cut-off sizes of cyclones at various sampling flow rates.

Type of Cyclone	Flow Rate (cfm)	Cut-off size (μm)	
		Experimental	Theoretical
T-1B	0.3	2.1	1.7
	0.5	1.3	1.05
	0.8	1.8	0.65
	1.0	1.0	0.51
T-2A	0.4	6.5	6.0
	0.6	2.6	3.6
	0.8	2.3	2.7
	1.0	2.6	2.2
T-3B	2.0	8.5	9
	2.5	4.7	7.5
	3.0	5	6.4

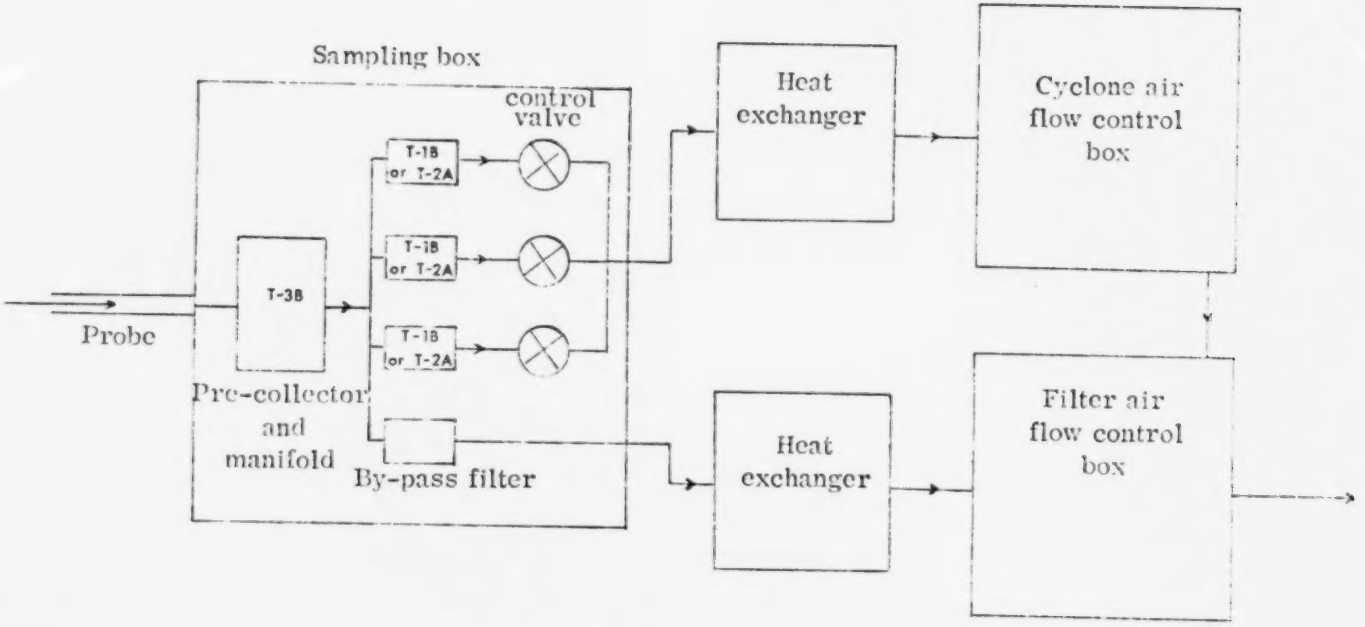

FIGURE 1. Block diagram of the McCrone parallel multicyclone sampling train.

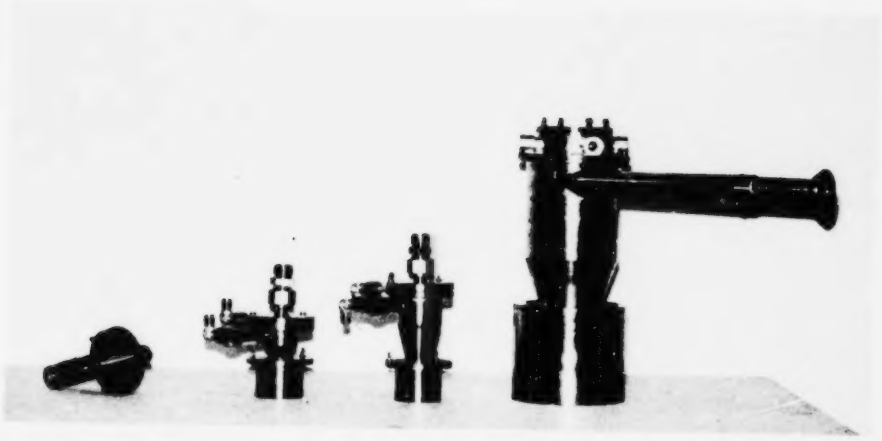

FIGURE 2 Shape and relative size of by-pass filter holder and sampling cyclones

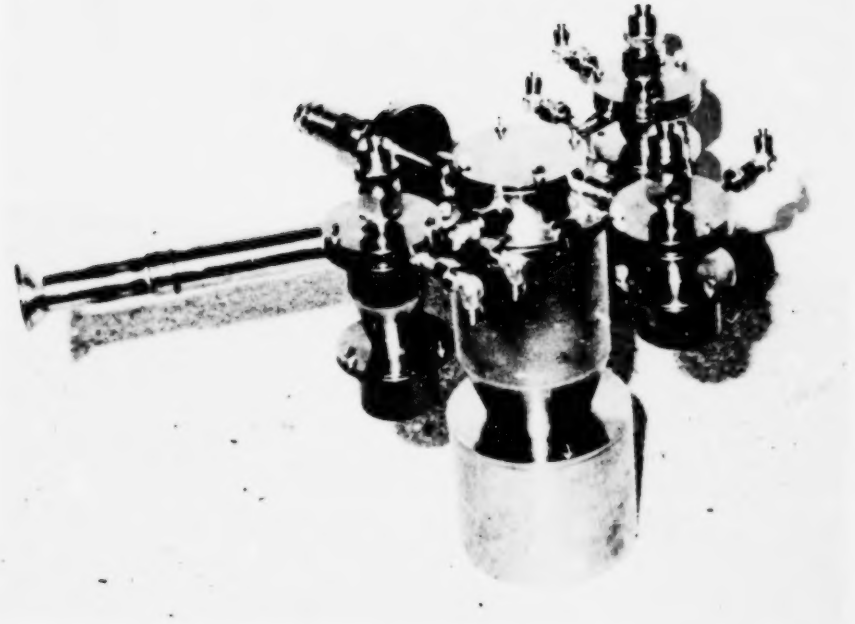

FIGURE 3 Assembly of sampling cyclones

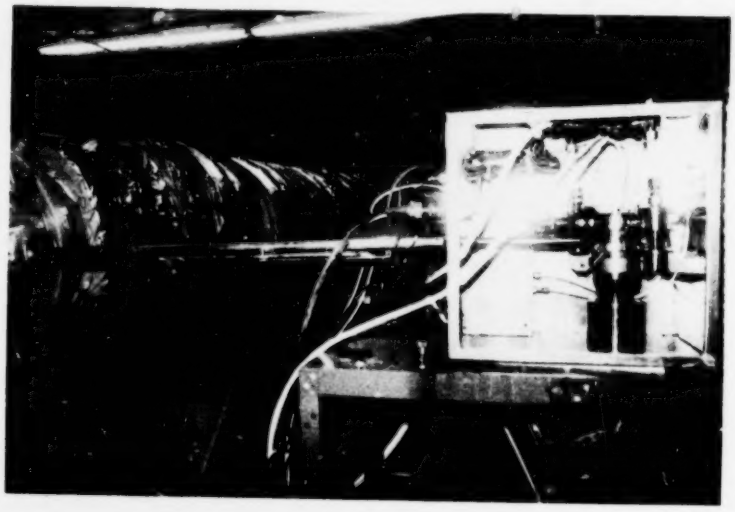

FIGURE 4 Assembled sampling box

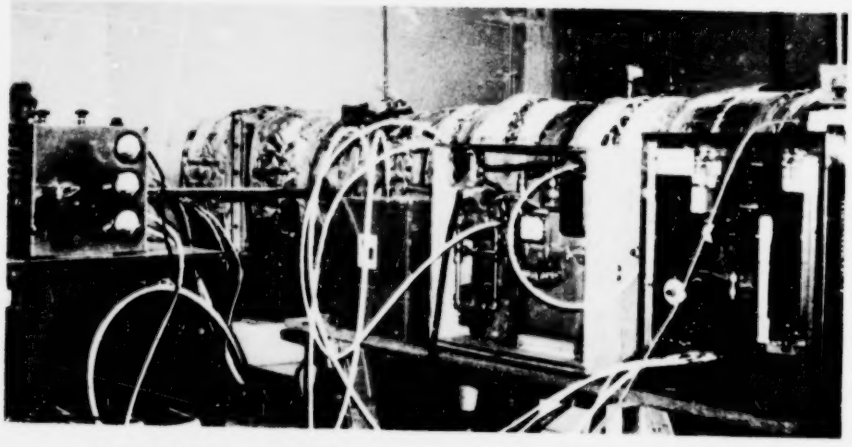

FIGURE 5 Complete train of parallel multicyclone particulate sampler

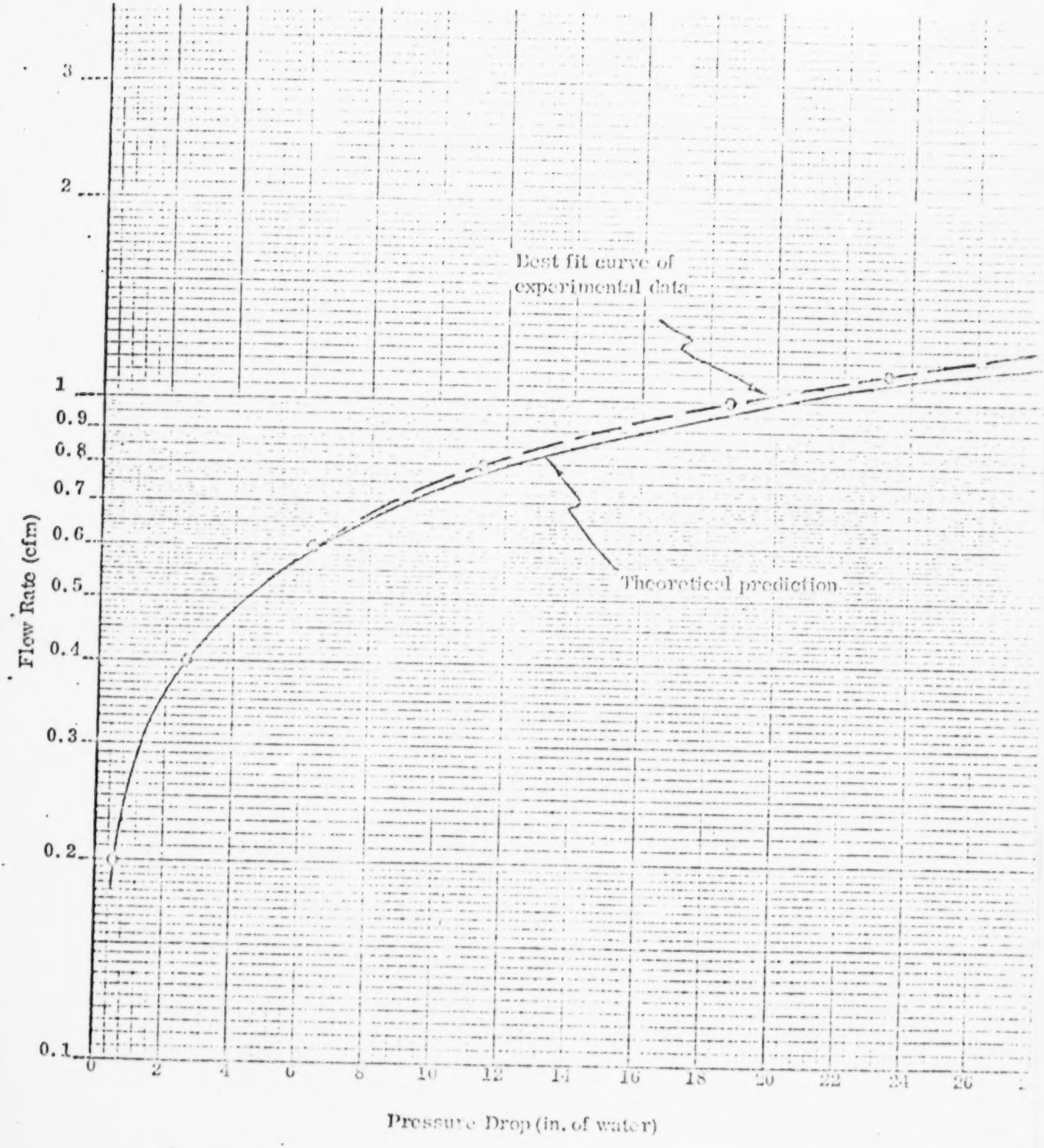

FIGURE 6 Comparison of actual pressure drop with theoretical pressure drop across cyclone T-13

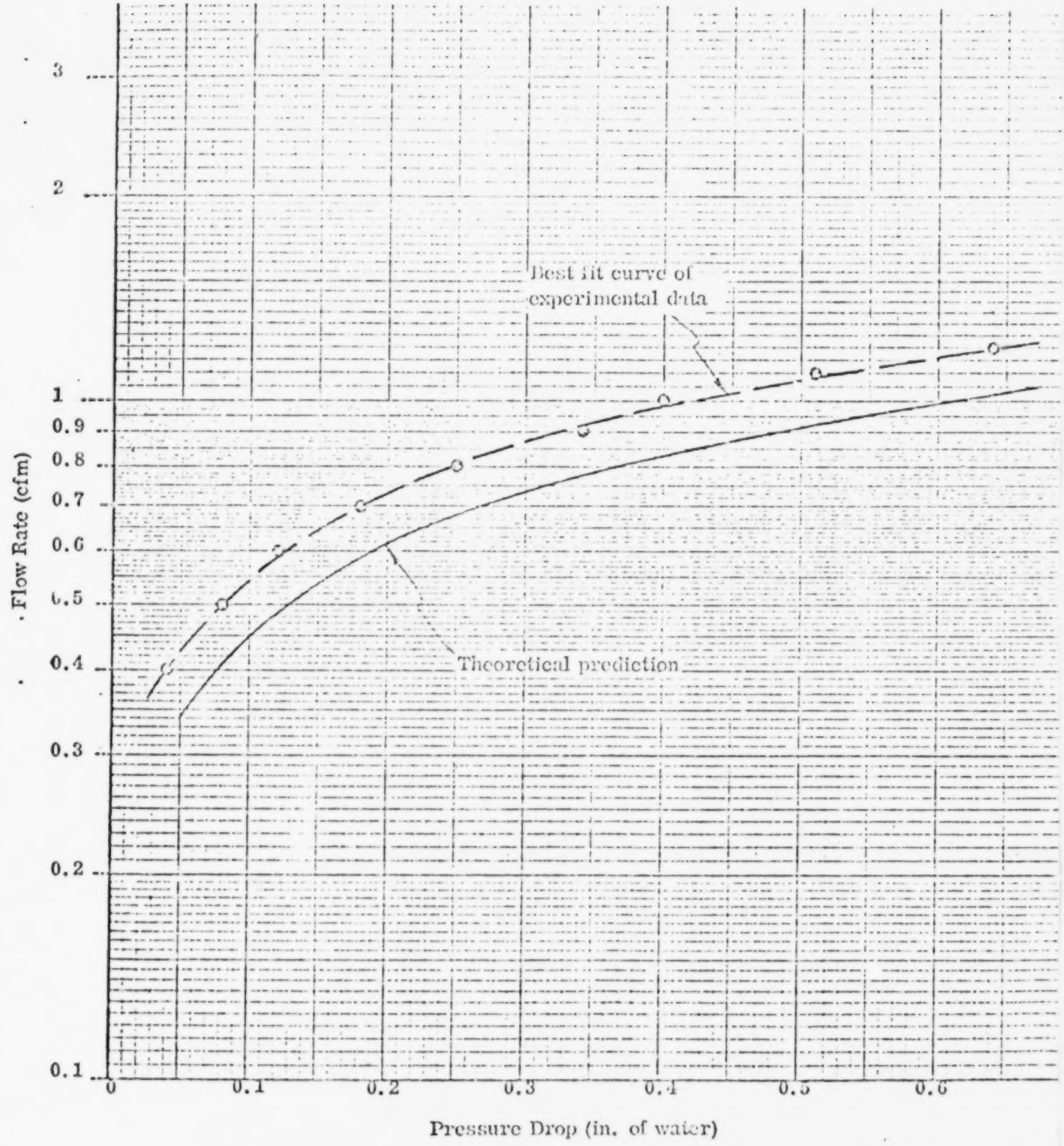

FIGURE 7 Comparison of actual pressure drop with theoretical pressure drop across cyclone T-2A

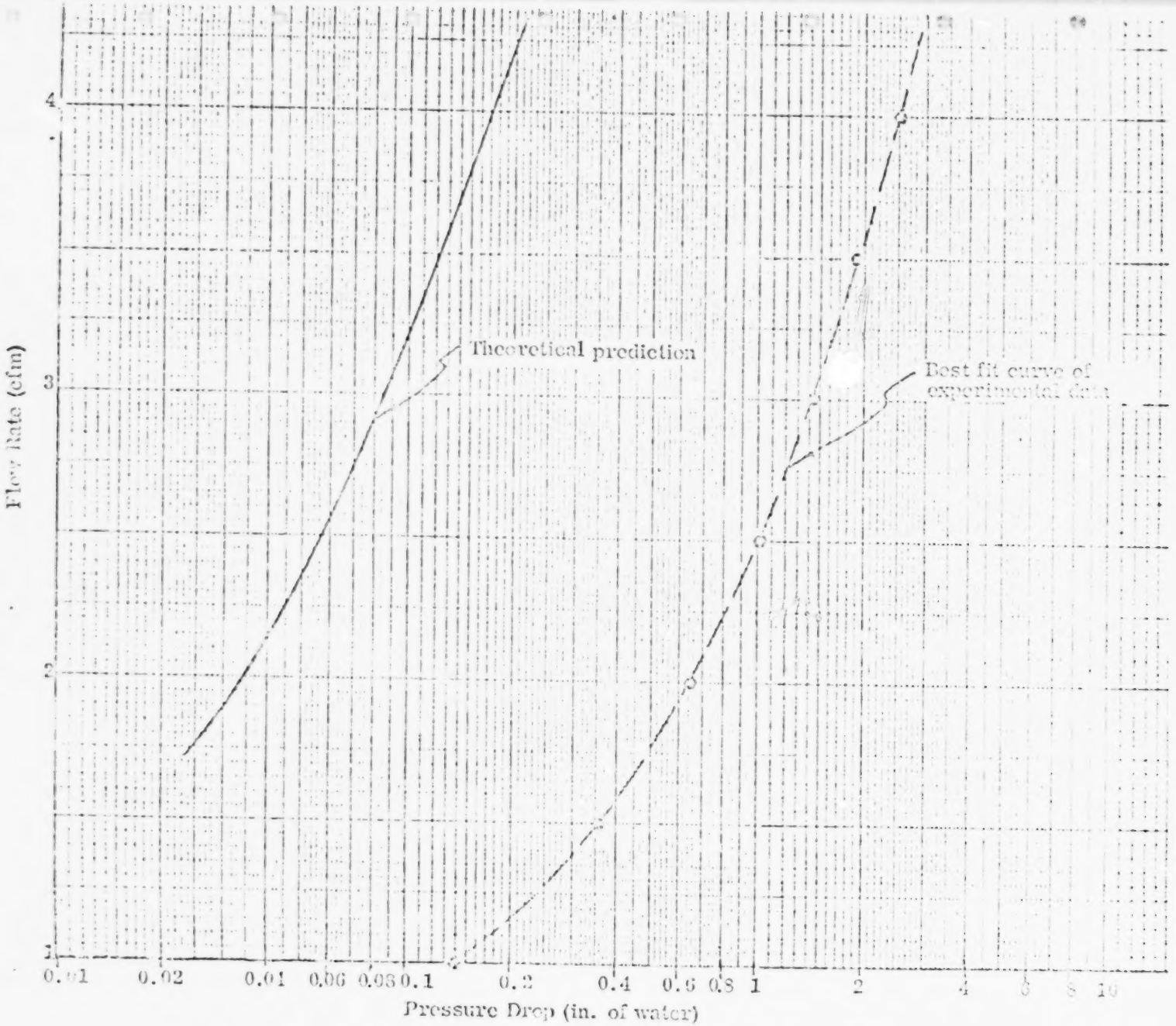

FIGURE 8 Comparison of actual pressure drop with theoretical pressure drop across cyclone T-3B and manifold

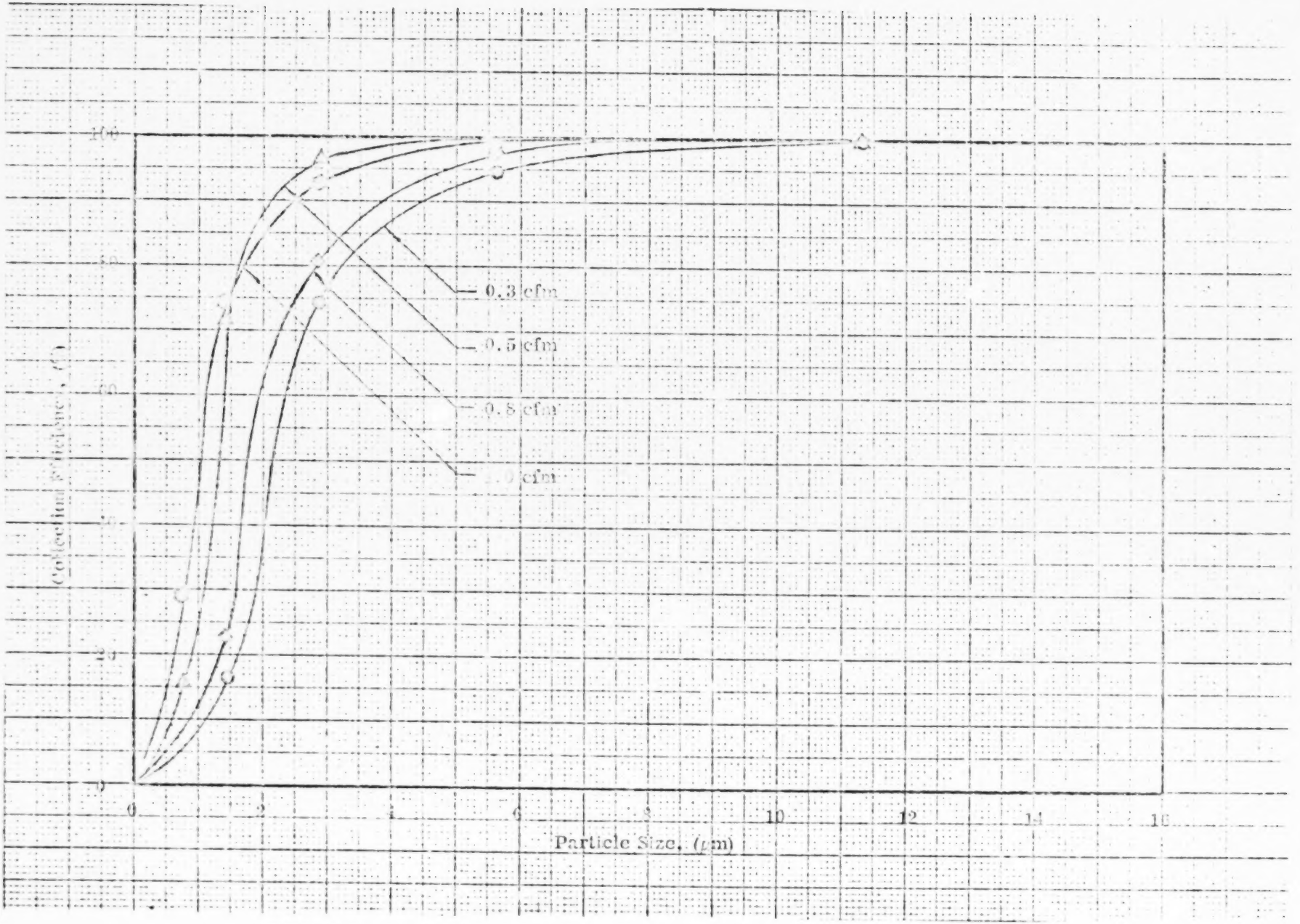

FIGURE 9 Particle collection efficiency of cyclone T-1B

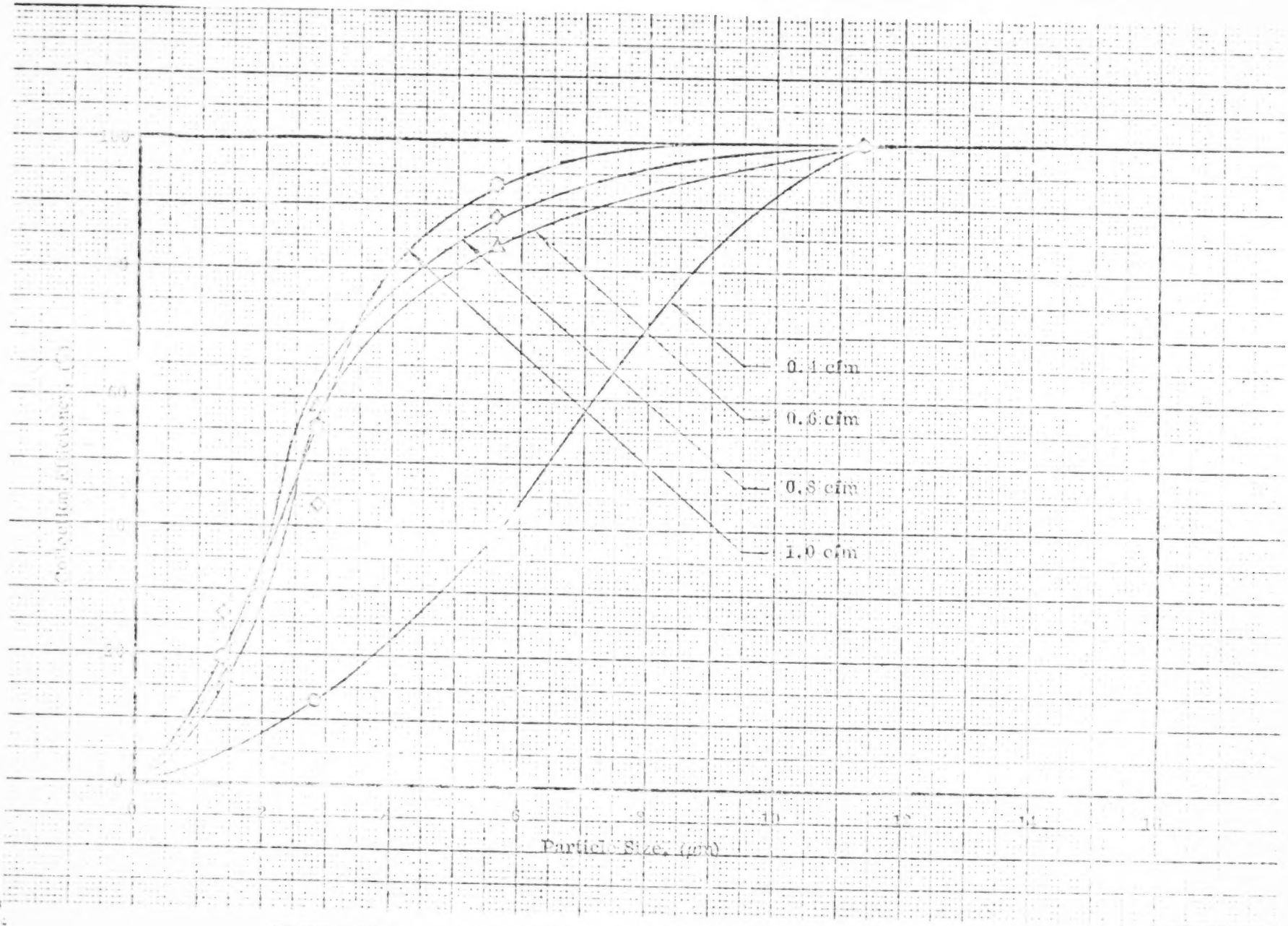

FIGURE 10 Particle collection efficiency of Cyclone T-2A

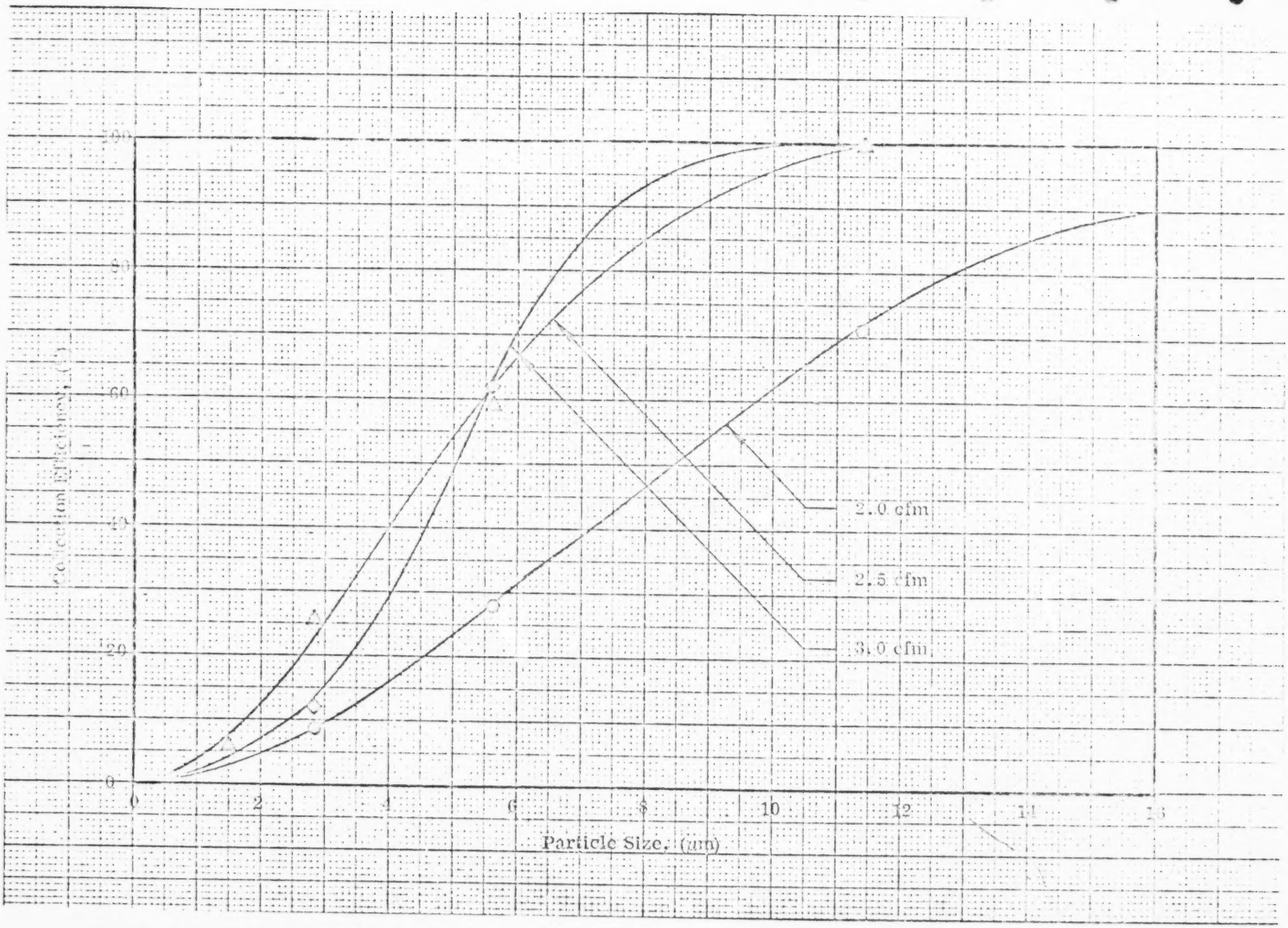

FIGURE 11 Particle collection efficiency of cyclone T-3B

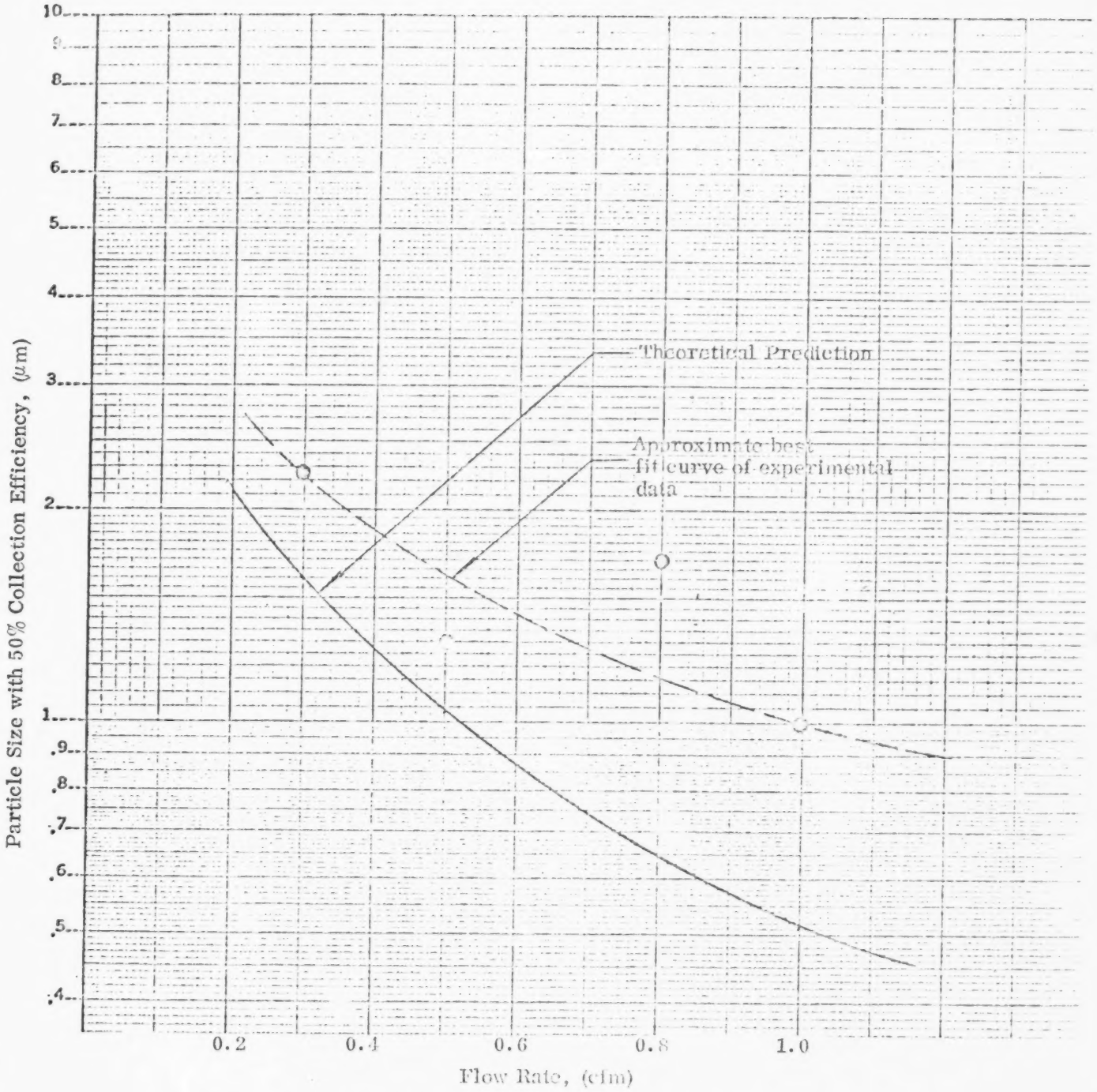

FIGURE 12 Comparison of experimental cut-off size with theoretical cut-off size of cyclone T-1B.

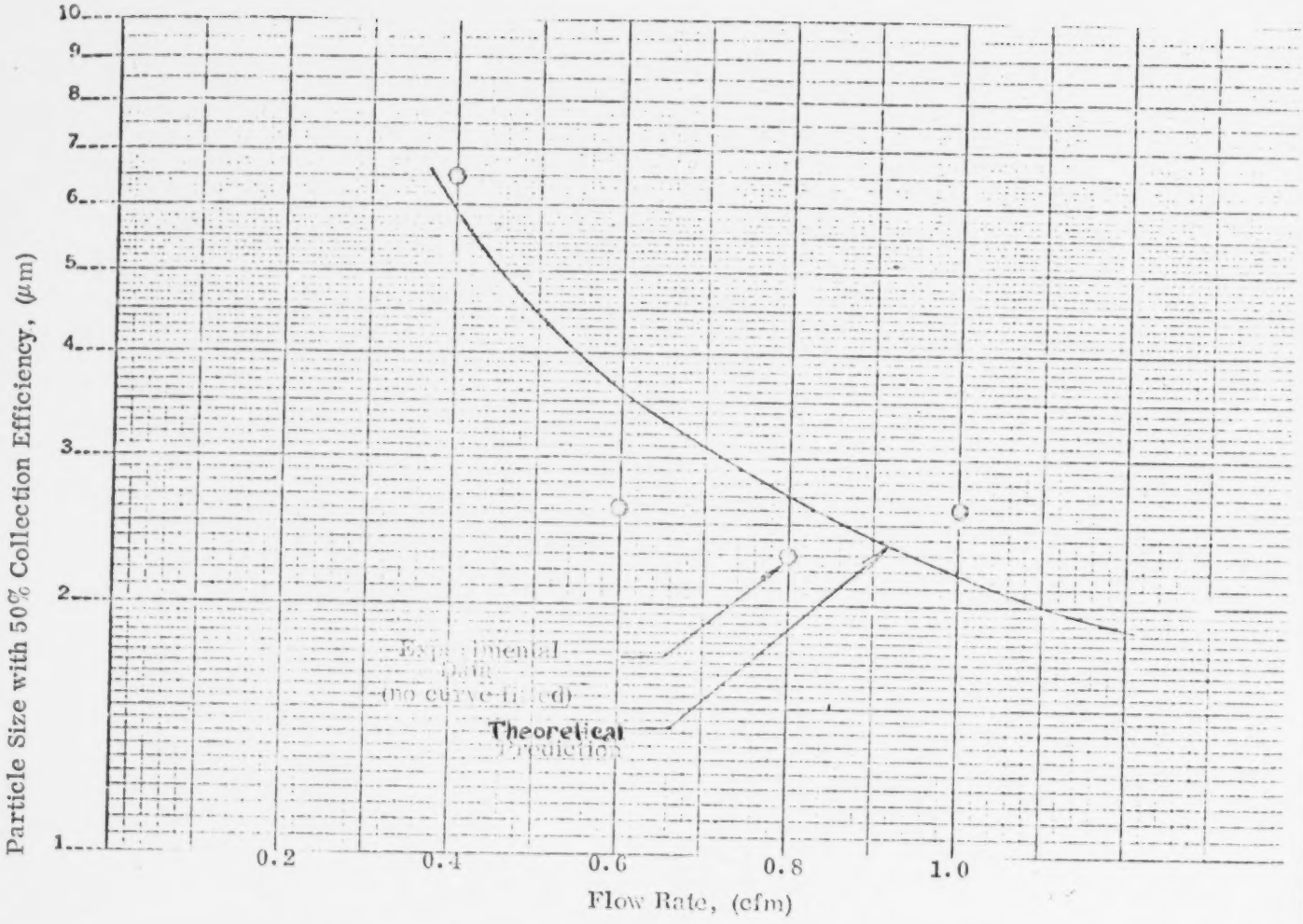

FIGURE 13 Comparison of experimental cut-off size with theoretical cut-off size of cyclone T-2A.

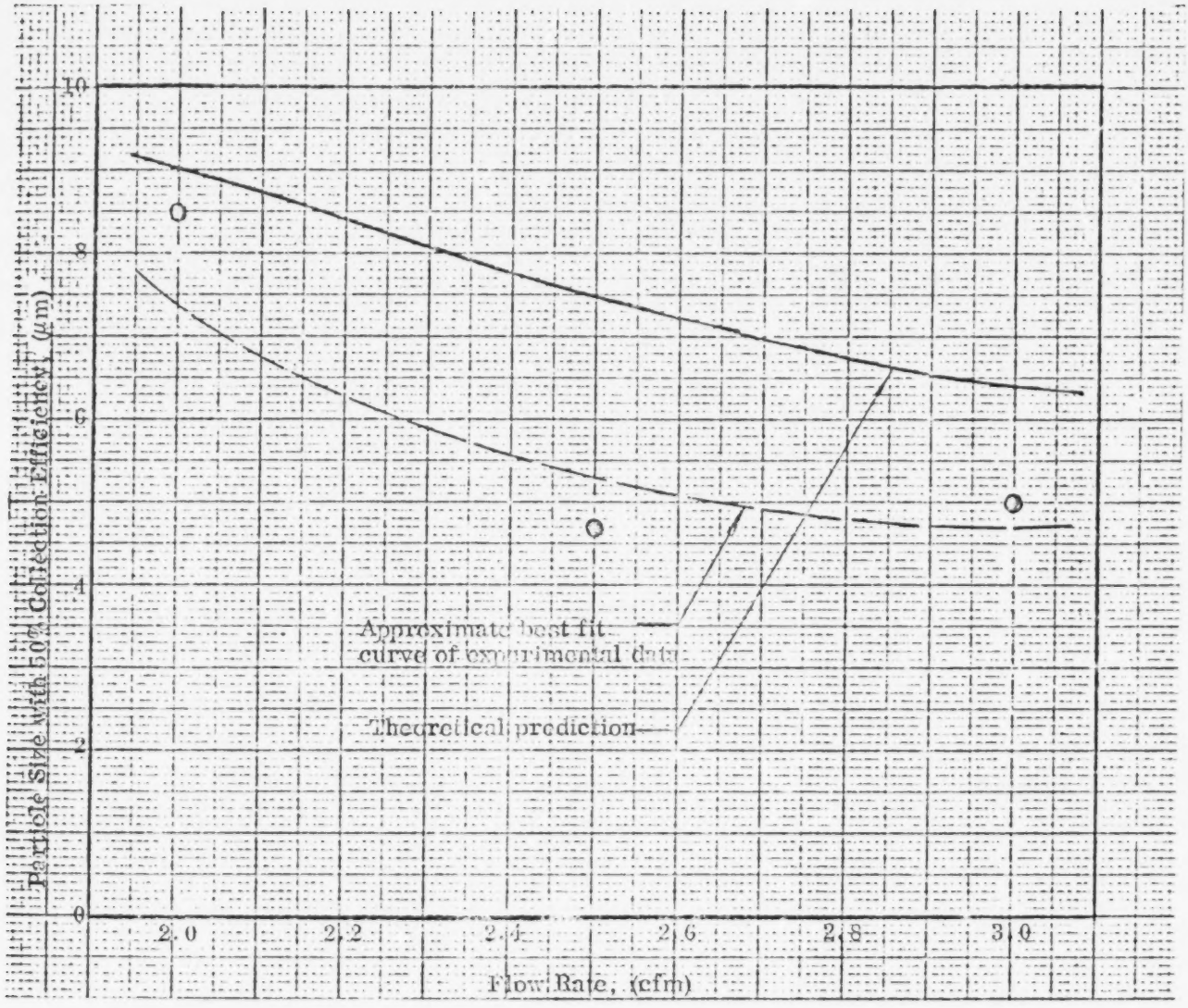

FIGURE 14 Comparison of experimental cut-off size with theoretical cut-off size of cyclone T-3B.

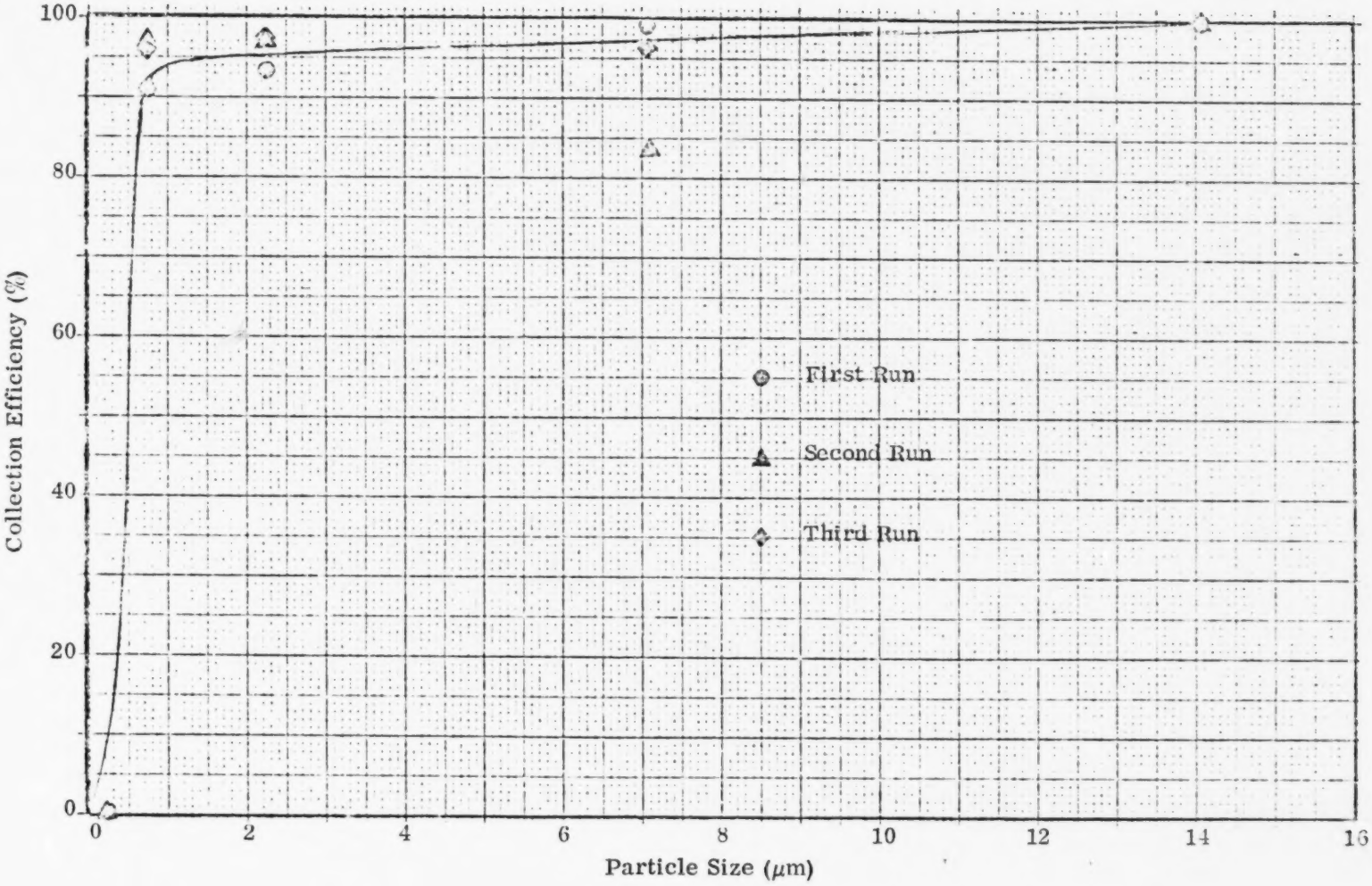

FIGURE 15 Particle collection efficiency of cyclone T-1B operated at a flow rate of 1.2 cfm

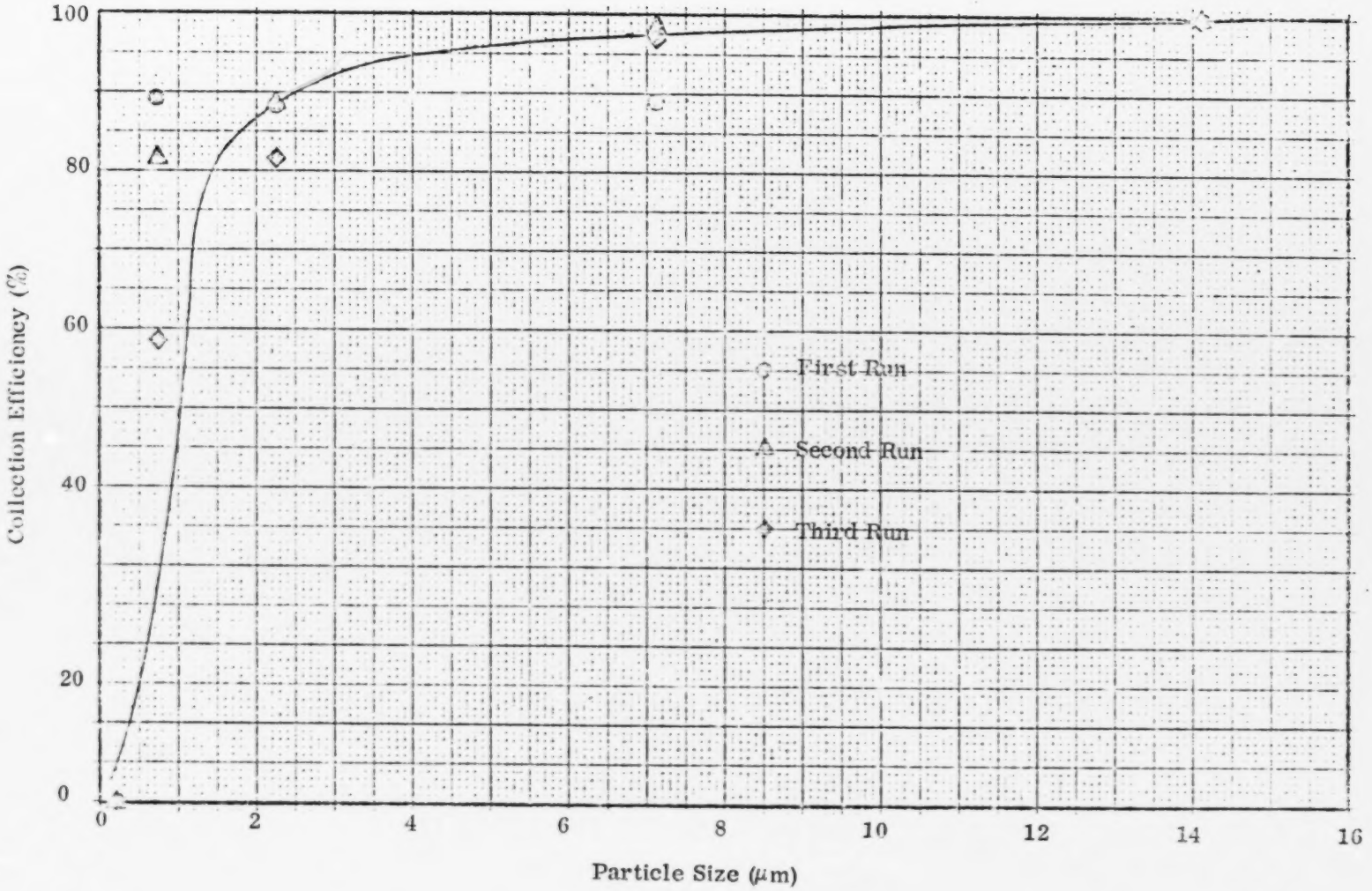

FIGURE 16 Particle collection efficiency of cyclone T-1B operated at a flow rate of 0.5 cfm

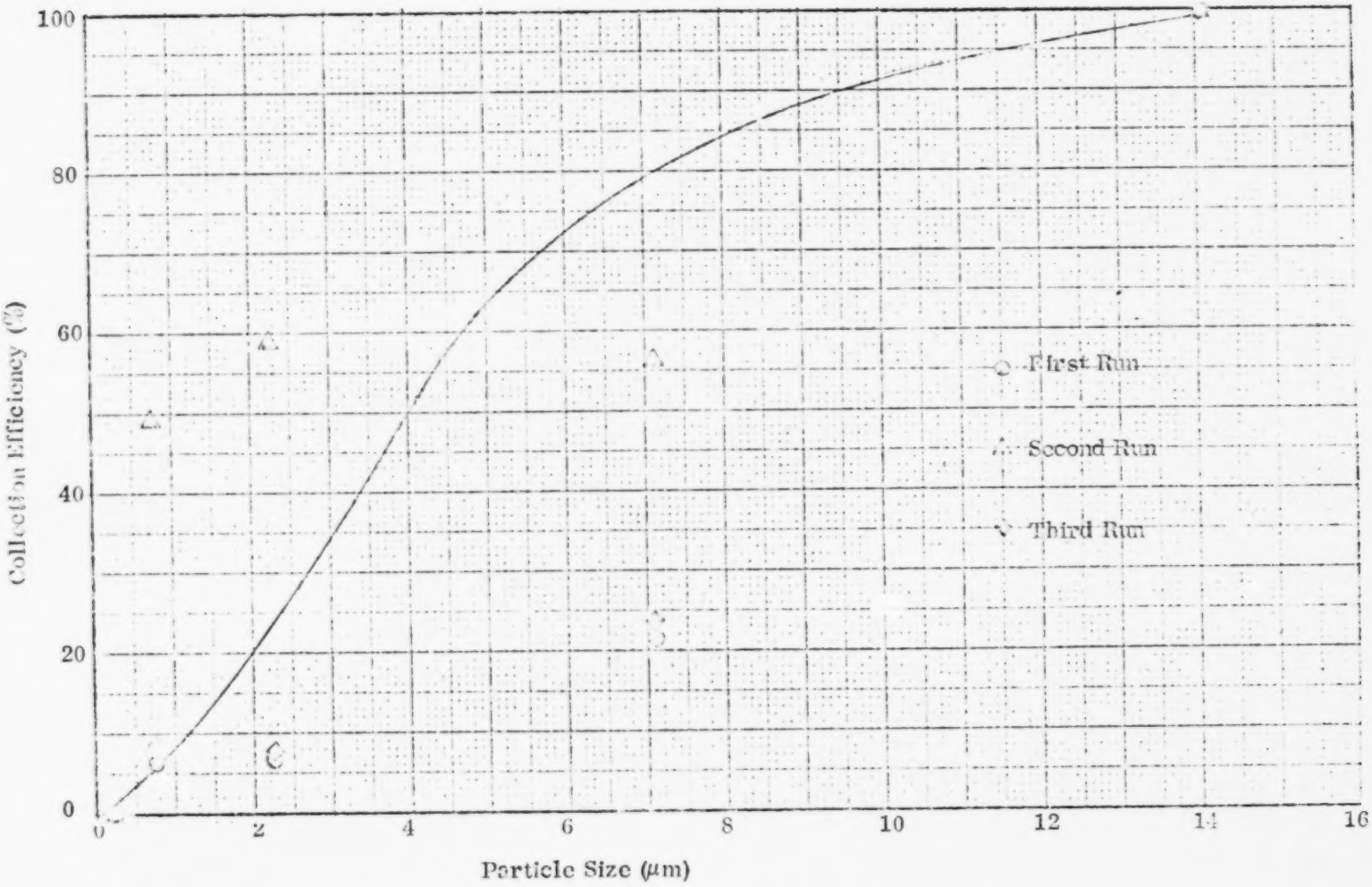

FIGURE 17 Particle collection efficiency of cyclone T-2A operated at a flow rate of 0.5 cfm

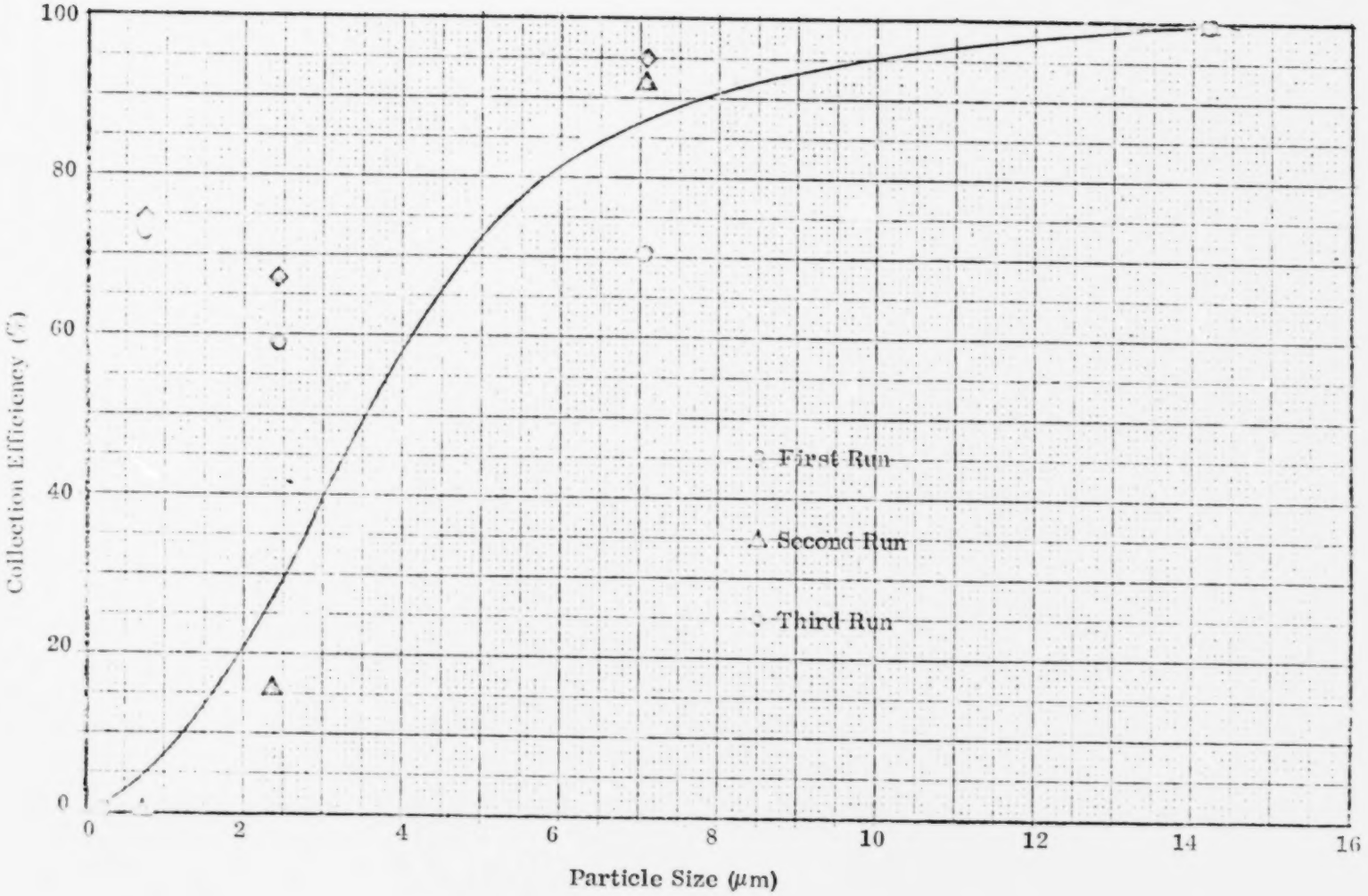

FIGURE 18 Particle collector efficiency of cyclone T-3B operated at a flow rate of 2.7 cfm

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